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POSSIBILITIES OF UTILISING NEWLY DEVELOPED NANOCRYSTALLINE MATERIALS AS STRESS AND FORCE SENSORS

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Abstract − Paper presents results of the investigation on the magnetoelastic properties of $Fe_{73.5}Nb_3Cu_1Si_{13.5}B_9$ alloy in amorphous and nanocrystalline state as stress and force sensor. The new method of applying stress to the ring core of sensor made of soft magnetic material such as nanocrystalline alloys is presented. In this method the distribution of stresses in the ring core is uniform, so even brittle magnetic materials (like nanocrystalline) may be used as stress sensors. The experimental results indicate that stress and force sensor applications require special parameters of the heat treatment of the sensing element. For this reason the optimal treatment parameters for the cores of inductive components should not be applied for cores of the stress sensors.

Keywords: stress and force sensor, magnetoelastic Villari effect, nanocrystalline alloys

1. INTRODUCTION

Nanocrystaline soft magnetic materials are known to be suitable for cores of inductive components [1]. Such materials can be also useful as cores of the magnetoelastic compressive stress and force sensors [2]. Due to a low magnetocrystalline anisotropy the high changes of magnetic parameters of nanocrystalline core subjected to mechanical stresses are expected. Moreover magnetoelastic Villari effect is critical for miniaturized inductive components. In such a case even small external forces may generate significant stresses in the core. For this reason properties of inductive components may be changed. Such external forces may be created in assembly of the component or as a result of a thermal dilatation. As a result the changes of the magnetic properties of the inductive component may produce significant changes in its functional parameters.

On the other hand significant stress sensitivity of the amorphous and nanocrystalline alloys creates possibility of utilizing this effect in construction of stress and force sensors. In a case of such sensors ferromagnetic material can be both sensing and construction element. In opposite to strain gauge sensors, in magnetolastic sensors, sensing element should not be mounted at elastic bar with adhesive layer. Moreover magnetoelastic stress and force sensors based on newly developed amorphous and nanocrystallie alloys (such as HITPERM) may operate in the high temperature range. Temperature of operation of such sensor is limited only by the Curie temperature. This temperature depends on alloy composition and can be about 600^0C for some alloys. As a result temperature of operation of magnetoelastic sensors can be significantly higher than strain-gauge sensors

For these reasons the influence of mechanical stresses caused by external forces on magnetic properties of the alloy (so called magnetoelastic Villari effect) is very important from practical point of view. The technological process (especially heat treatment), which is optimal for achieving good magnetic properties of the material may lead to the increasing of the stress sensitivity of the amorphous or nanocrystalline alloy. Due to this fact, the magnetoelastic properties of such materials should be taken into consideration in time of the development of the technology of the production. In spite of this assumption the results of investigation of the influence of the nanocrystalisation process on magnetoelastic properties (especially magnetoelastic Villari effect) of the most commonly used $Fe_{73.5}Nb_3Cu_1Si_{13.5}B_9$ alloy seems to be still not presented.

2. PHYSICAL BACKGROUND OF MAGNETOELASTIC VILLARI EFFECT

Total free energy E of the magnetic material subjected both magnetizing field H and mechanical external stresses σ may be given as a sum of the free energies of the material [3]:

$$E = E_H + E_D + E_K + E_\sigma \tag{1}$$

where: E_H is connected with the magnetizing field energy , E_D is demagnetising energy, E_K is total anisotropy energy and E_σ is magnetoelastic energy.

Magnetoelastic energy E_σ can be also considered as a stress induced anisotropy energy K_u^σ and is given by the equation [4]:

$$E_\sigma = K_u^\sigma = \frac{3}{2}\lambda_s \sigma \sin^2\phi = K_\sigma \sin^2\phi \tag{2}$$

where stress induced anisotropy constant K_σ is equal 3/2 $\lambda_s\sigma$. The angle between magnetizing field H and direction of material magnetization M is noted as ϕ.

The way, in which material responds on mechanical, external stresses is determined by equation (2). According to the commonly accepted notation the tensile stresses are marked as positive and the compressive stresses are marked as negative.

When the product $\lambda_s\sigma > 0$ (for example material with positive magnetostriction λ_s is subjected to tensile stresses σ) the magnetoelastic energy is minimal when magnetization vector M is parallel to the stresses σ ($\phi = 0^o$ or 180^o). Therefore if magnetizing field H is parallel to the stresses, the value of flux density B in the magnetized material is higher than in unstressed material.

When the product $\lambda_s\sigma < 0$ (for example material with positive magnetostriction λ_s is subjected to compressive stresses σ) the magnetoelastic energy is minimal when magnetization vector M is perpendicular to the stresses σ ($\phi = 90^o$ or 270^o). Therefore if magnetizing field H is parallel to the stresses, the value of flux density B in the magnetized material is lower than in unstressed material.

In a case, when external stresses σ are not parallel to the magnetizing field H, a value of the effective stress σ_{eff} (which influence on the magnetic properties of the material) may be calculated from the equation (3) [4, 5]:

$$\sigma_{eff} = \sigma(\cos\varphi - \nu\sin\varphi) \quad (3)$$

where ν is Poison ratio and φ is the angle between external stress σ direction and direction of the magnetizing field H.

3. METHODS OF APPLYING STRESS TO THE MAGNETOELASTIC SENSING ELEMENT

In a case of nanocrystalline magnetoelastic stress sensors, the method of applying stresses to the sensing element is the most important. Nanocrystalline magnetic alloys are produced as the ribbon ring cores. For this reason the frame-shape core [6], which is effective for bulk magnetic materials (i.e. ferrites), can not be applied. In previously presented methods of utilizing amorphous or nanocrystalline materials as the stress sensors, the compressive force was applied in the direction of the diameter of the ring-shape core or strips of the material was used.

The idea of applying compressive stress to the ring-shape core in the direction of the diameter is presented in Fig. 1 [7, 10].

In such a case value of stresses in the core can be calculated from equation [8]:

$$\sigma = \frac{3rF}{wN_t h^2}\left(\frac{2}{\pi} - \cos\theta\right) \quad (4)$$

where N_t – is the number of turns of the strip in the core, h and w are thickness and wide of strip, E –Young modulus of the alloy and θ describes point, in which stresses are calculated.

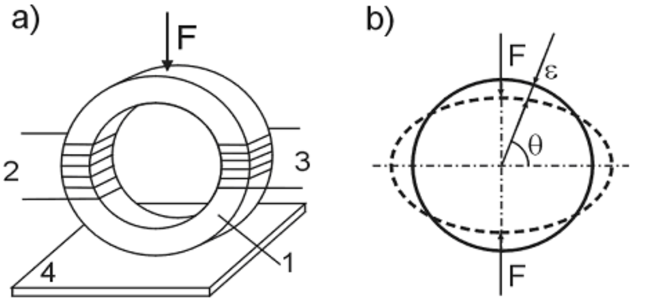

Fig. 1. a) Idea of applying the compressive force in the direction of the diameter of the ring-shape sensing element: 1) base plane, 2) magnetizing winding, 3) sensing winding, 4) sensing core, b) schematic diagram of displacement ε in the core under influence of the external force F

When stresses are applied in the direction of the diameter of the ring-shaped core the distribution of the stress is nonunirom. As a result highly stressed areas are present in the sample. For this reason the magnetoelastic properties of the brittle nanocrystalline materials can not be investigated with this method. Moreover due to the fact, that both tensile and compressive stresses are present in the sensing element, the stress sensitivity of the sensor is significantly reduced [9].

Another presented previously method of utilizing the amorphous and nanocrystalline alloys as the stress sensors was connected with applying stresses to the strip sample glued to the nonmagnetic, bent bar [10]. In such a case results depend on the shape of the sample. Moreover due to the appearance of the demagnetisation energy (caused by open magnetic circuit of the strip) in the total free energy of the material sensitivity of such sensor is significantly limited.

As a result for utilizing nanocrystalline alloys as a stress and force sensors new method of applying stresses to the core should be developed. This new method, presented in the paper, enable utilizing nanocrystalline ribbon ring cores as the compressive stress and force sensor. The general idea of applying compressive stress to the amorphous ring cores is presented in Fig. 2. A compressive force F is applied to the ring core perpendicular to the direction of the magnetizing field [9]. In this method a uniform and known value of the compressive stresses σ in the sample can be reached. Moreover, the magnetic circuit is closed hence the value of strength of magnetic field can be simply calculated. The demagnetization process may also be performed electrically.

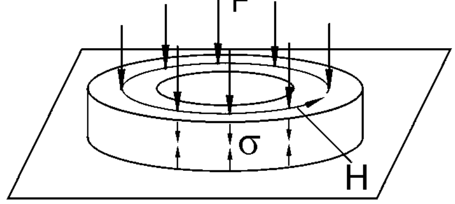

Fig. 2. General idea of applying the compressive stress to the ribbon ring core.

A special device for the application of stresses to the ring core [9] is presented in Fig. 3. Base backings (3) allow a ring core (1) to be subjected of compressive force *F*. Due to the special cylindrical backing (2) the stresses in the core are uniform. Measuring and magnetizing windings are placed in grooves (2a) at the cylindrical backings (2).

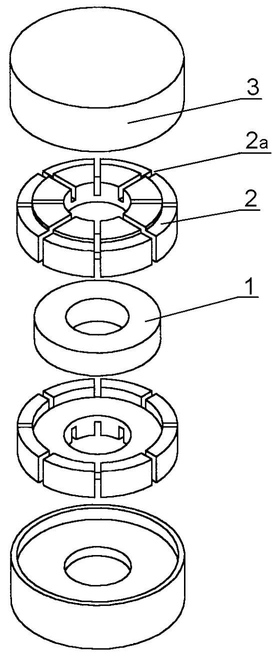

Fig. 3. Device for applying the compressive stress to the ribbon ring core (Patent pending P-345758). 1 – core under investigation, 2 – cylindrical backing, 2a – grooves for windings, 3 – base backing.

In this method of applying stresses both of a bulk material rings and ribbon ring cores can be investigated. Because of the uniform distribution of stresses in the sample the high local stresses are absent. For this reason also a brittle material such as nanocrystalline materials can be investigated.

4. NANOCRYSTALLINE ALLOY AS A MAGNETOELASTIC SENSING MATERIAL

Presented new method was used to investigate the magnetoelastic properties of the ring core made of $Fe_{73.5}Nb_3Cu_1Si_{13.5}B_9$ alloy both in amorphous and nanocrystalline state. The outside diameter of the cores were 30 mm the inside diameter was 20 mm and the height was 10 mm.

The nanocrystalline structure was achieved by thermal annealing. The sample no. 1 was in amorphous state, samples no. 2 and no. 3 were annealed respectively in 450^0C and 550^0C for 1 hour to achieve nanocrystalline structure. After thermal annealing significant decreasing of the coercive field H_c was observed. In as-quenched sample coercive field H_c was equal 25 A/m. During the annealing value of H_c (for major hysteresis loop at H = 30 A/m) decreased to 2 A/m and 1 A/m for samples annealed for 1 hour respectively in temperatures 450^0C and 550^0C. Moreover after thermal annealing the value of initial permeability μ_i increased form 425 to 58200 and 50000 respectively. Due to the fact, that anisotropy K of the sample is connected with the value of initial permeability μ_i, these results confirmed that heat annealing have significant influence on anisotropy of the samples. As a result it have significant influence on both total free energy E of the samples and its stress sensitivity.

5. EXPERIMENTAL RESULTS

The method of measurement influence of compressive stresses σ on a quasi-static hysteresis loop was described in a recent publication [2]. The experiment was performed at room temperature for compressive stresses up to 10 MPa.

The $B(\sigma,H)$ relation was measured with the following procedure: the sample was demagnetized, next stressed and then the quasi-static hysteresis loop $B(H)_\sigma$ measured. Then the $B(\sigma)_H$ was calculated from the hysteresis loops $B(H)_\sigma$.

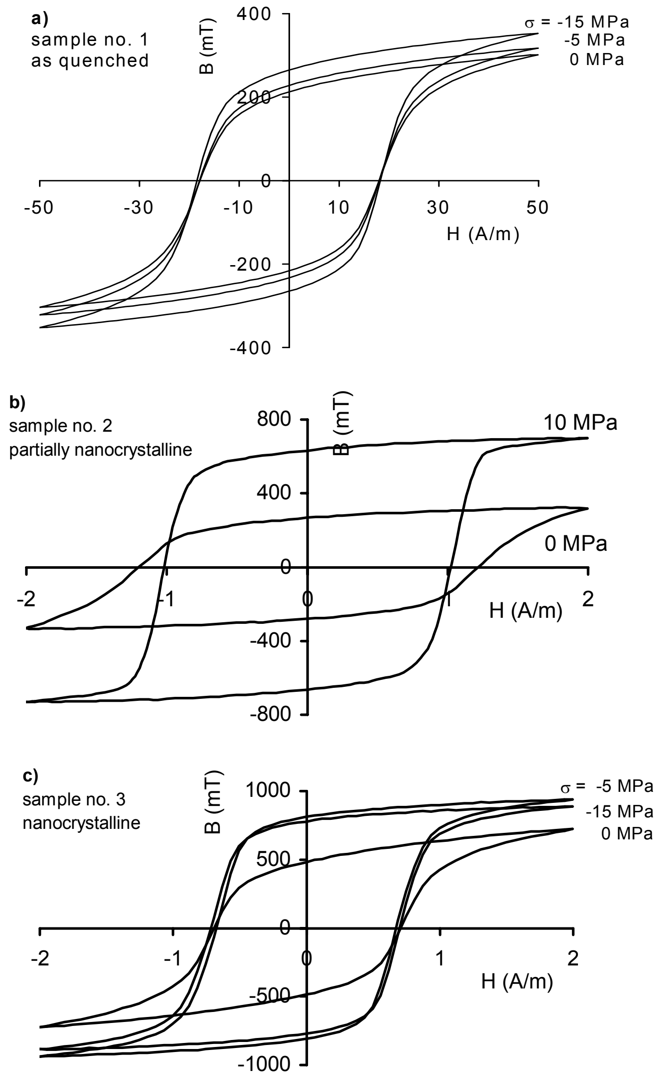

Fig. 4 Influence of the compressive stress σ on quasistatic hysteresis loop of the core made of $Fe_{73.5}Nb_3Cu_1Si_{13.5}B_9$ no.1 – as quenched state, no. 2 – after annealing 450^0C / 1h (partially nanocristalised), no.3 - after annealing 550^0C (in nanocrystalline state)

The influence of stresses on the hysteresis loop of the $Fe_{73.5}Nb_3Cu_1Si_{13.5}B_9$ samples is presented in Fig. 4. Under influence of the compressive stresses σ = 10 MPa the flux density *B* of the sample no. 2 increases about 100% and the value of the coercive force H_c decreases significantly. The hysteresis loop tends to become narrower. For the samples no. 1 and 3 changes are also significant, but smaller.

Changes in the flux density *B* of the investigated cores, as a function of compressive stresses *σ*, are presented in Fig. 5. The measurements were carried out for constant values of the magnetizing field *H*, two times higher than coercive force H_c of each sample (H=2 H_c).

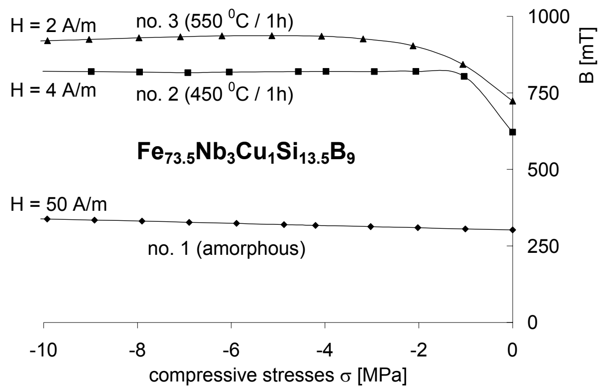

Fig. 5 $B(\sigma)_{H=2Hc}$ relations for the $Fe_{73.5}Nb_3Cu_1Si_{13.5}B_9$ cores in amorphous (no. 1) and nanocrystalline (no. 2 and 3) state

As it is presented in Fig. 5 thermal annealing has significant influence on the magnetoelastic $B(\sigma)_H$ characteristics. For sample in as-quenched state this characteristic is approximately linear. Sample no 2 (partially nanocrystalised) has high stress sensitivity in the initial range of stresses. Moreover both annealed samples has non-monotonous $B(\sigma)_H$ dependences. This information should be taken into consideration in construction of the magnetoelastic stress and force sensors based on the sensing elements made of $Fe_{73.5}Nb_3Cu_1Si_{13.5}B_9$ alloy.

6. CONCLUSION

Due to the presented, special system of force conversion, the uniform distribution of the compressive stress in the ring-shaped core of magnetoelastic sensors can be achieved. As a result the high local stresses are absent. Therefore, higher values of compressive stresses can be reached even in brittle, nanocrystalized cores.

Presented results confirm that newly developed, soft magnetic $Fe_{73.5}Nb_3Cu_1Si_{13.5}B_9$ alloy, both in amorphous and nanocrystalline state can be used as compressive stress and force sensing element.

Achieved results indicate that thermal treatment influence significantly on the magnetoelastic properties of the $Fe_{73.5}Nb_3Cu_1Si_{13.5}B_9$ alloy. Moreover the optimal thermal treatment for inductive element applications (sample no. 3) is not optimal from the point of view of magnetoelastic sensors construction. This effect should be taken in consideration by constructors of the magnetoelastic sensors based on nanocrystalline materials.

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